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Determinants of Dust Exposure in Tunnel Construction Work

Berit Bakke,[1] Patricia Stewart,[2] and Wijnand Eduard[1]
[1]National Institute of Occupational Health, Oslo, Norway; [2]Division of Cancer Etiology and Genetics, National Cancer Institute, Rockville, Maryland

In tunnel construction work, dust is generated from rock drilling, rock bolting, grinding, scaling, and transport operations. Other important dust-generating activities are blasting rock and spraying wet concrete on tunnel walls for strength and finishing work. The aim of this study was to identify determinants of dust exposure in tunnel construction work and to propose control measures.

Personal exposures to total dust, respirable dust, and α-quartz were measured among 209 construction workers who were divided into 8 job groups performing similar tasks: drill and blast workers, shaft drilling workers, tunnel boring machine workers, shotcreting operators, support workers, concrete workers, outdoor concrete workers, and electricians. Information on determinants was obtained from interviewing the workers, observation by the industrial hygienist responsible for the sampling, and the job site superintendent. Multivariate regression models were used to identify determinants associated with the dust exposures within the job groups.

The geometric mean exposure to total dust, respirable dust, and α-quartz for all tunnel workers was 3.5 mg/m^3 (GSD = 2.6), 1.2 mg/m^3 (GSD = 2.4), and 0.035 mg/m^3 (GSD = 5.0), respectively. A total of 15 percent of the total dust measurements, 5 percent of the respirable dust, and 21 percent of the α-quartz exceeded the Norwegian OELs of 10 mg/m^3, 5 mg/m^3, and 0.1 mg/m^3, respectively. Job groups with highest geometric mean total dust exposure were shotcreting operators (6.8 mg/m^3), tunnel boring machine workers (6.2 mg/m^3), and shaft drilling workers (6.1 mg/m^3). The lowest exposed groups to total dust were outdoor concrete workers (1.0 mg/m^3), electricians (1.4 mg/m^3), and support workers (1.9 mg/m^3). Important determinants of exposure were job group, job site, certain tasks (e.g., drilling and scaling), the presence of a cab, and breakthrough of the tunnel. The use of ventilated, closed cabs appeared to be the single most important control measure for lowering exposures.

Keywords Tunnel, Construction Workers, Construction Industry, Exposure Assessment, Determinants, Total Dust, Respirable Dust, α-Quartz

In tunnel construction work, dust is generated from rock drilling, rock bolting, grinding, scaling, and transport operations. Other important dust-generating activities are blasting rock and spraying wet concrete on tunnel walls for strength and finishing work.

As a part of an epidemiological cohort study on the relationship between exposure and obstructive lung disease in Norwegian tunnel workers, a large exposure survey was performed between 1996 and 1999 to estimate personal exposure levels. We have previously described job groups and reported exposure levels.(1) We found considerable differences in exposure levels between the job groups. We also reported an increased risk of obstructive pulmonary disease in these workers.(2)

Information on determinants of exposure is crucial because, when used in conjunction with measurement data, it allows for a more accurate exposure assessment of workers compared with using only measurement data and/or observations. The better data should, in turn, facilitate a more rigorous exposure evaluation, which should improve accuracy.(3,4) Increased accuracy improves the effectiveness of identifying priorities for reducing exposures in order to reduce health risks. Determinants are also important factors for grouping of workers by exposure levels in epidemiological studies.

In some studies of exposure in the construction industry a task-based exposure assessment strategy has been used successfully to identify factors that contribute to exposure.(5–8) However, few published studies have evaluated factors that contribute to exposure in tunnel construction work.(9–10) In this article we describe the results of further analyses of the exposure data from our study of tunnel construction workers(1) in order to identify determinants of dust exposure and to propose control measures.

MATERIALS AND METHODS

Sampling Strategy and Job Groups

Between 1996 and 1999 16 different tunnel construction sites were visited, and measurements of dust exposure were performed. Prior to measurement, the tunnel workers had been divided into job groups in which the workers performed similar tasks. The groups consisted of workers excavating (drill and blast workers, shaft drilling workers, tunnel boring machine [TBM] workers); workers performing protection and securing work (shotcreting operators who apply wet concrete, support workers); and workers performing finishing work (concrete workers, electricians). Other concrete workers, who worked outside the tunnel, served as an internal reference group in the epidemiological study.[2] A random sample of workers from each job group was measured. Exposure to dust was determined by personal sampling and the aim was to measure exposure to two or more agents for each person for at least two days. Under the labor agreements of the workers the work shift was 10 hours with two breaks of 30 minutes each. The sampling time was limited to 5–8 hours because of the limited battery capacity of the sampling equipment. High dust concentrations further increased power consumption. However, the sampling time was considered representative for the whole work shift because the sampling periods were selected randomly within a shift and tasks were often repeated on the same day. A more detailed description of sampling strategy and job groups has been reported elsewhere.[1]

Determinants

Information on potential determinants within each job group was obtained from three sources: 1) the workers themselves, 2) the industrial hygienist responsible for the sampling, and 3) the job site superintendent. The workers were interviewed after the sampling was completed about the type and the duration of the tasks they had performed during the sampling. In addition, they were asked for their perception of the exposure conditions. The industrial hygienist observed the workers throughout the sampling period and recorded information such as the type of operator cab. The job site superintendent provided general information about the construction site: the size of the tunnel, the type of explosives, and the type of equipment used. The superintendent also provided information on unusual occurrences during the sampling, such as the temporary shutdown of ventilation fans and special tasks.

Dust Exposure

Total dust was collected on acrylic copolymer membrane filters (Versapore 800, Gelman Sciences, Ann Arbor, MI), with a 0.8 μm pore size, fitted in 25 mm closed-face aerosol filter cassettes (Gelman Sciences) at a sampling flow rate of 2 L min^{-1}. Respirable dust was collected on 37 mm cellulose acetate filters with a pore size of 0.8 μm using a cyclone separator (Casella T13026/2, London, U.K.) at a sampling flow rate of 2.2 L min^{-1}.

The particle mass was measured with a microbalance (Sartorius AG, MC 210 p, Goettingen, Germany), with a detection limit of 0.06 mg (0.063 mg/m^3 based on 8 hour sampling).

The α-quartz content in the respirable dust sample was measured by X-ray diffraction using NIOSH Method 7500.[11]

Data Analysis

Measured exposure values were used without further adjustment for the unsampled time because they were regarded as representative of the whole work shift. Using cumulative probability plots, the exposure data were best described by lognormal distributions. The exposure data were therefore ln-transformed before further statistical analyses. Standard measures of central tendency and distributions (arithmetic means [AM], geometric means [GM], medians, and geometric standard deviations [GSD]) were calculated. For statistical tests a significance level of 0.05 was chosen.

The GM is calculated from the arithmetic mean of the log-transformed exposures, AM_{logX}, by exp (AM_{logX}). The GSD is calculated similarly from the standard deviation of the log-transformed exposures, SD_{logX}, by exp (SD_{logX}).[4] The GM has to be divided and multiplied with the GSD to obtain confidence limits; for example, the lower and upper 95 percent confidence limits are approximately GM/GSD^2 and $GM*GSD^2$, respectively.

Differences in exposure levels among the job groups were evaluated using Kruskal-Wallis test because the Levene's test showed that variances were not homogeneous ($p < 0.05$). The analysis of the important determinants for each job group started with univariate models using t-tests and one-way analysis of variance (ANOVA) of the categorical variables suspected of influencing the personal exposure levels. The determinants evaluated were: season, work shift, job site, cross-section of the tunnel (<50, 50–100, >100 m^2), equipment (no cab, open cab, closed cab), work height (ground level, >5 m above ground level), the type of explosive, the type of accelerator, before versus after breakthrough of the tunnel to the other side, and operation of TBM machine (yes/no). Only those determinants with sufficient measurements are reported. The means of different strata of the determinants were compared using Bonferroni's post hoc tests. In case of heteroscedasticity the Kruskal-Wallis test was used instead of ANOVA and the Mann-Whitney test instead of t-tests and Bonferroni post hoc tests.

The duration of the tasks was described by the percentage of the total sampling time. Correlations between continuous predictor variables (i.e., task duration as the percentage of the total sampling time) were evaluated using Pearson's correlation coefficient. No variables were excluded from the modeling because no correlation coefficient exceeded 0.6. Multivariate regression models were developed for each job group using a forward stepwise regression procedure.[12] Job tasks occurring with a frequency of $n \leq 3$ were not included in the analysis. The model was built in steps beginning with the variable with the lowest p-value and adding variables (p to enter <0.20) until further additions did not result in statistically significant p-values for the added variables (p to remove >0.10), earlier variables lost their significance, or the regression coefficients changed by more than 10 percent. Finally, plausible interactions between explanatory variables were added and kept in the model when a partial F test was significant ($p < 0.05$).[12] All measurements were considered as independent observations in the analysis. Residuals were studied to assess the fit of the final model. All data analyses were performed using SYSTAT 9.0 and SPSS 10.0 (SPSS Inc., Chicago, IL).

RESULTS

In total 209 workers participated in the exposure study and most of the workers (77%) were monitored on more than one occasion. The geometric mean exposure of total dust, respirable dust, and α-quartz for all tunnel workers was 3.5 mg/m^3 (GSD = 2.6), 1.2 mg/m^3 (GSD = 2.4), and 0.035 mg/m^3 (GSD = 5.0), respectively (Table I). Comparison of job groups by the Kruskal-Wallis test showed statistical differences among the groups for each of the three agents ($p < 0.01$). The geometric mean exposure levels of total dust in the job groups varied from 1.0 (outdoor concrete workers) to 6.8 (shotcreting operators) mg/m^3. The geometric mean exposure levels of respirable dust varied from 0.20 (outdoor concrete workers) to 2.8 (shaft drilling workers) mg/m^3, and the geometric mean exposure levels of α-quartz varied from 0.002 (outdoor concrete workers) to 0.39 mg/m^3 (TBM workers).

Determinants

Two of the tunnel construction sites investigated were associated with power plants, four with railway installations, seven with road construction, one with a sports center, and two with cleaning/purification plants. The cross-section area of the tunnels varied from 13 m^2 (in a shaft) to 340 m^2 (a rock cavern). Information on the season, work shift, and job site was available for most job groups. Other determinants evaluated were, for example, the type of equipment used and tasks performed (Table II). The percentage of time spent on different tasks by the job groups during the air monitoring are given in Table III. On average, the workers carried out two to three primary tasks during the sampling.

Drill and Blast Workers

The type of drill rig was a major determinant of all three types of exposures when drilling was performed for >1.0 hours. Workers using a drill rig with no operator cab had the highest exposure to total dust (7.1 mg/m^3), which was significantly different from the exposures resulting from using an open cab (2.0 mg/m^3) or a closed cab (1.6 mg/m^3), $p < 0.05$ (Table IV). Similar patterns were found for the respirable dust and α-quartz exposure.

Statistical modeling of the determinants of exposure indicated that the tasks of mechanical scaling (removal of loose rock using a hydraulic jackhammer), shotcreting, drilling (with no cab), and repairing the ventilation duct increased the total dust exposure level, while assisting with the drilling operation (e.g., detaching the drill head when it was stuck in the drilling hole, etc.) was associated with a decreased exposure (Table V). Mechanical scaling and drilling with no cab also were associated with increased respirable dust exposure levels, while repair work (repairing equipment), drilling assistance, performing "miscellaneous tasks" (e.g., tidying up work area, organizing equipment, etc.), manual scaling (removal of loose rock using hand tools), and rock bolting were associated with decreased exposures. For α-quartz exposure, drilling (with no cab), shotcreting, mucking (gathering of the rock using a shovel), transport of the rock out of the tunnel, and repairing the ventilation duct were associated with increased exposures, while rock bolting was associated with decreased exposures. These models for the drill and blast workers explained 27–38 percent of the variance of the three types of dust exposures.

Shotcreting Operators

The shotcreting operators essentially performed only one task. They sprayed wet concrete (shotcrete) onto the tunnel walls for rock support either during the excavation process to protect the workers from falling rock (before tunnel breakthrough) or after the excavation has been completed for permanent rock support (after breakthrough). Effects on exposure of the type of shotcreting rig used were studied before breakthrough, and was an important determinant of exposure (Table VI). The geometric mean exposure of the workers using shotcreting rigs with closed cabs was 85 percent (total dust) and 73 percent (respirable dust) lower than operators using no cabs ($p < 0.05$). Workers using open cabs were exposed to dust levels that were between these two types of shotcreting rigs.

Performing shotcreting before or after tunnel breakthrough when using an open cab was an important determinant of exposure (Table VI). The geometric mean exposure of the shotcreters after tunnel breakthrough was 78 percent lower for total dust compared to that before breakthrough ($p < 0.01$), but no significant difference was found for respirable dust. The type of accelerator had a small and nonsignificant effect on both total dust and respirable dust exposures. No variable had a significant effect on α-quartz exposure.

Statistical modeling of the determinants of total dust exposure showed that the presence of a cab and whether the job was performed before or after tunnel breakthrough were determinants associated with decreased exposure (Table VII). For respirable dust exposures only the presence of a cab was associated with decreased exposures. These models explained 66 and 52 percent of the variance of the dust exposures (Table VII), respectively. No significant models for α-quartz exposure were found.

TABLE III

Percentage of time spent on different tasks by tunnel construction workers during sampling as reported by the workers. Numbers in bold are tasks including three or less measurements

Task	Drill and blast workers %[A]	Shotcreting operators %	TBM workers %	Concrete workers %	Outdoor concrete workers %	Electricians %	Shaft drilling workers %	Support workers %
Carpentry				**17**	43			
Charging of explosives	8							**0.5**
Cleaning				**0.7**	**7**			
Concrete mixing	**0.2**							
Concreting				8	**0.3**			
Demolition				7	11			
Drilling assistance	8				**0.8**			**11**
Drilling	14			3			74	35
Electric fitting	**0.8**					52		**6**
Grinding				0.8	**2**			
Injection concrete	**0.8**							
Iron work				26	23			
Miscellaneous	**7**		12[B]	27	**6**	21		**5**
Mucking/hauling	17							
Repair work	5		18[C]	**0.6**			**26**	
Rock bolting	5							**4**
Manual scaling	10							25
Mechanical scaling	4							
Shotcreting	3	98						**1**
Spraying of oil	**0.1**	**0.1**		**0.1**	**7**			**0.1**
TBM electrician			19[C]					
TBM loading surveillance			24[C]					
TBM operator			25[C]					
Torch cutting				0.7				
Transport/driving	11					7		5
Ventilation repair	3							6
Welding				2	**1**	**5**		
Outdoors[D]	4	2	1	8		16		3

[A]Average percentage of time during which the task was carried out, based on 5–8 hour sampling.
[B]Tunnel boring machine operated, includes three measurements when the tunnel boring machine was not operated.
[C]Tunnel boring machine operated.
[D]Amount of time the tunnel workers were outside the tunnels while sampling was being performed.

TABLE IV
Exposure of drill and blast workers to total dust, respirable dust, and α-quartz by type of drilling rig

	Total dust, mg/m^3			Respirable dust, mg/m^3			α-Quartz, mg/m^3		
Type of drilling rig	n[A]	GM[B]	GSD[C]	n	GM	GSD	n	GM	GSD
No cab	7		1.9	7		1.4	3		1.7
Open cab	8		2.0	8		1.4	8		1.7
Closed cab	22		2.0	23		1.9	23		2.9

[A]Number of measurements.
[B]Geometric mean.
[C]Geometric standard deviation.
[D,E]Pairs of significantly different means between work conditions using Bonferroni post hoc tests ($p < 0.05$).

TBM Workers

The TBM workers did not operate the tunnel boring machine every day due to repair work on the TBM machine and on the ventilation ducts. When the TBM was operated, the workers had significantly higher exposure levels for all three agents than when the machine was not operated ($p < 0.001$) (Table VIII). The geometric mean exposure of the workers when the TBM was not operated was 81 percent (total dust), 79 percent (respirable dust), and 90 percent (α-quartz) lower than when the TBM was operated. There were no significant differences in exposures between work shifts (when operating the TBM), but exposures were lower during the day compared to evening shifts. The respirable dust exposures while operating the TBM were 50–70 percent lower in the summer ($p < 0.01$) than during the

TABLE V
Multiple linear regression models of tasks performed related to total dust, respirable dust, and α-quartz exposures in drill and blast workers

Agent	Tasks	Regression coefficient[A]	Standard error	p
Total dust	Intercept	0.72	0.078	<0.001
$R^2_{adj} = 0.27, n = 113$	Mechanical scaling, %[B]	0.025	0.008	<0.01
	Shotcreting, %	0.015	0.006	<0.05
	Drilling (no cab), %	0.013	0.004	<0.01
	Ventilation repair, %	0.011	0.004	<0.01
	Drilling assistance, %	−0.006	0.003	<0.05
Respirable dust	Intercept	0.22	0.097	<0.05
$R^2_{adj} = 0.30, n = 117$	Mechanical scaling, %	0.012	0.006	<0.05
	Drilling (no cab), %	0.007	0.004	0.06
	Repair work, %	−0.007	0.004	0.05
	Drilling assistance, %	−0.008	0.003	<0.01
	Miscellaneous, %	−0.010	0.004	<0.01
	Manual scaling, %	−0.012	0.004	<0.01
	Rock bolting, %	−0.017	0.004	<0.001
α-Quartz	Intercept	−4.14	0.122	<0.001
$R^2_{adj} = 0.38, n = 113$	Drilling (no cab), %	0.059	0.013	<0.001
	Shotcreting, %	0.016	0.007	<0.05
	Mucking, %	0.014	0.003	<0.001
	Transport, %	0.013	0.003	<0.001
	Ventilation repair, %	0.012	0.005	<0.05
	Rock bolting, %	−0.016	0.005	<0.01

[A]The regression coefficient yields a factor with which the background level (intercept) should be multiplied to calculate the estimated geometric mean. For example, a worker who performs 60 percent mechanical scaling and 40 percent drilling assistance during a work shift would have an estimated total dust exposure of: $\exp^{(0.72+0.025*60-0.006*40)} = \exp^{(0.72)} * \exp^{(0.025*60)} * \exp^{(-0.006*40)} = 2.05 * 4.48 * 0.79 = 7.3$ mg/m^3.
[B]% = Percent time.

TABLE VI
Exposure of shotcreting operators to total dust, respirable dust, and α-quartz by type of rig, tunnel breakthrough, and type of accelerator

	Total dust, mg/m^3			Respirable dust, mg/m^3			α-Quartz, mg/m^3		
	n^A	GM^B	GSD^C	n	GM	GSD	n	GM	GSD
Type of shotcreting rig (before tunnel breakthrough)									
Closed cab	21	2.1^{D,E}	1.8	20	1.1^D	1.7	4	0.035	4.3
Open cab	8	8.5^D	1.7	10	1.2^E	3.0	9	0.012	4.4
No cab	46	13.7^E	1.7	48	4.0^{D,E}	1.6	27	0.013	2.3
Tunnel breakthrough (open cab)									
After (tunnel open at two ends)	7	1.9^F	3.2	6	1.2	1.8	5	0.012	4.4
Before (tunnel open at only one end)	8	8.5^F	1.7	10	1.2	3.0	9	0.012	4.4
Accelerator (no cab)									
Waterglass, Na_4SiO_4, pH = 11–13	10	16.2	1.4	10	4.8	1.3	4	0.014	1.9
Alkali free, $Al_2(SO_4)_3$, pH = 2–3	36	13.0	1.8	38	3.7	1.6	23	0.012	2.4
(closed cab)									
Waterglass, Na_4SiO_4, pH = 11–13	14	2.2	2.0	13	1.1	1.8	4	0.035	4.3
Alkali free, $Al_2(SO_4)_3$, pH = 2–3	7	1.9	1.2	7	1.0	1.6	G		

[A]Number of measurements.
[B]Geometric mean.
[C]Geometric standard deviation.
[D,E]Pairs of significantly different means between shotcreting rigs using Mann-Whitney tests ($p < 0.05$).
[F]Pairs of significantly different means between before and after tunnel breakthrough using t-tests ($p < 0.01$).
[G]No measurement.

winter and spring season, whereas no difference in total dust and α-quartz exposure was found by season, although similar patterns were observed.

Statistical modeling of the measurement results showed that the "miscellaneous tasks" and surveillance of loading broken rock onto the conveyor belt were determinants associated with increased total dust, respirable dust, and α-quartz exposure on days when the TBM machine was operated. These models explained 10–17 percent of the variability in exposure (Table IX).

Tunnel Concrete Workers

Tunnel concrete workers at site A (a railway installation) had significantly higher exposures compared to those same workers at other sites (cleaning/purification plants and a sport center) for the three measured agents ($p < 0.001$) (Table X). The geometric mean exposures of the workers at the other sites (B, C, D) were 48 percent (total dust), 55 percent (respirable dust), and 87 percent (α-quartz) lower than those of workers at job site A. The height that the work was being done had no significant influence on exposure. Measurements on both work shifts (day and

TABLE VII
Multiple linear regression models of determinants related to total dust and respirable dust exposure in shotcreters

Agent	Determinants	Regression coefficient^A	Standard error	p
Total dust	Intercept	2.62	0.092	<0.001
$R^2_{adj} = 0.66$, n = 81	Closed cab (0/1)	−1.88	0.16	<0.001
	Open cab (0/1)	−0.47	0.24	0.05
	Breakthrough (0/1)	−1.48	0.32	<0.001
Respirable dust	Intercept	1.37	0.085	<0.001
$R^2_{adj} = 0.52$, n = 84	Closed cab (0/1)	−1.30	0.16	<0.001
	Open cab (0/1)	−1.18	0.17	<0.001

[A]The regression coefficient yields a factor with which the background level (intercept) should be multiplied to calculate the estimated geometric mean. For example, a worker who performs shotcreting by using an open cab after breakthrough of the tunnel would have an estimated total dust exposure of: $\exp^{(2.62-0.47-1.48)} = \exp^{(2.62)} * \exp^{(-0.47)} * \exp^{(-1.48)} = 13.74 * 0.63 * 0.23 = 2.0$ mg/m^3.

TABLE VIII

Exposure of TBM workers to total dust, respirable dust, and α-quartz by operating TBM (yes vs. no), work shift, and season

	Total dust, mg/m^3			Respirable dust, mg/m^3			α-Quartz, mg/m^3		
	n^A	GM^B	GSD^C	n	GM	GSD	n	GM	GSD
Operating TBM?									
Yes	38	7.0^D	1.7	40	2.2^D	1.8	40	0.46^D	2.1
No	3	1.3^D	1.4	3	0.46^D	1.9	3	0.046^D	2.1
Work shift (operating TBM)									
Day (6:00 am–4:00 pm)	10	5.5	2.1	11	1.8	1.9	11	0.43	2.2
Evening (4:00 pm–2:00 am)	28	7.6	1.5	29	2.4	1.7	29	0.47	2.0
Season (operating TBM)									
Fall	6	5.3	1.3	8	2.3	1.2	8	0.31	1.6
Winter	3	11.2	1.8	3	4.0^F	1.6	3	0.81	1.5
Spring	21	7.3	1.8	22	2.4^E	1.8	22	0.58	2.1
Summer	8	6.6	1.4	7	1.2^{E,F}	1.4	7	0.28	1.9

[A]Number of measurements.
[B]Geometric mean.
[C]Geometric standard deviation.
[D]Pairs of significantly different means between operating the TBM versus not operating the TBM using t-tests ($p < 0.001$).
[E,F]Pairs of significantly different means between seasons using Bonferroni post hoc tests ($p < 0.05$).

evening) were only performed at site A. For this site, there was no significant difference in exposure between the work shifts for any of the measured agents.

Statistical modeling of the determinants of total dust exposures found that job site A and the task of welding were associated with increased exposures of the tunnel concrete workers. Working at job sites A and B increased the respirable dust exposures, while the tasks of concreting and demolition of wooden forms containing the concrete decreased exposures. An interaction between the task of demolition and job site B was found for respirable dust, indicating an increased exposure when performing this task at job site B compared to other job sites. For α-quartz exposure the job sites A, B, and C, were associated with increased exposure levels, while the tasks of demolition, drilling, and outdoor work were associated with decreased exposures. These models explained 36–85 percent of the variance of the dust exposures (Table XI).

Outdoor Concrete Workers

The geometric mean exposure of the outdoor concrete workers was 71 percent (total dust), 78 percent (respirable dust), and 94 percent (α-quartz) lower than the tunnel concrete workers (Table I). The geometric mean exposures of total dust,

TABLE IX

Multiple linear regression models of determinants related to total dust, respirable dust, and α-quartz exposures in TBM workers

Agent	Determinants	Regression coefficient^A	Standard error	p
Total dust	Intercept	1.74	0.104	<0.001
$R^2_{adj} = 0.17$, n = 38	Miscellaneous, %^{B}	0.006	0.002	<0.01
	Loading surveillance, %	0.004	0.002	<0.05
Respirable dust	Intercept	0.607	0.112	<0.001
$R^2_{adj} = 0.10$, n = 40	Miscellaneous, %	0.005	0.002	<0.05
	Loading surveillance, %	0.004	0.002	0.05
α-Quartz	Intercept	−1.02	0.141	<0.001
$R^2_{adj} = 0.14$, n = 40	Miscellaneous, %	0.008	0.003	<0.05
	Loading surveillance, %	0.005	0.003	0.09

[A]The regression coefficient yields a factor with which the background level (intercept) should be multiplied to calculate the estimated geometric mean. For example, a worker who performs 60 percent miscellaneous tasks and 40 percent loading surveillance during a work shift would have an estimated total dust exposure of: $\exp^{(1.74+0.006*60+0.004*40)} = \exp^{(1.74)} * \exp^{(0.006*60)} * \exp^{(0.004*40)} = 5.70 * 1.43 * 1.17 = 9.5$ mg/m^3.
[B]Percent time.

TABLE X

Exposure of tunnel concrete workers to total dust, respirable dust, and α-quartz by job site, work height, and work shift

	Total dust, mg/m^3			Respirable dust, mg/m^3			α-Quartz, mg/m^3		
	n[A]	GM[B]	GSD[C]	n	GM	GSD	n	GM	GSD
Job site									
Site A	27	5.4[D]	1.4	30	1.6[D]	1.4	30	0.087[E]	1.6
Sites B–D	68	2.8[D]	1.5	64	0.72[D]	1.9	26	0.011[E]	4.4
Work height									
Ground level	77	3.3	1.7	75	0.90	2.1	51	0.031	4.5
>5 m above ground	18	3.4	1.5	19	1.0	1.5	5	0.057	4.0
Work shift (site A)									
Day (6:00 am–4:00 pm)	7	3.2	1.3	7	2.0	1.3	7	0.112	1.3
Evening (4:00 pm–2:00 am)	20	5.2	1.4	23	1.5	1.4	23	0.081	1.6

[A]Number of measurements.
[B]Geometric mean.
[C]Geometric standard deviation.
[D]Pairs of significantly different means between job sites using Bonferroni post hoc tests ($p < 0.05$) (total dust and respirable dust).
[E]Pairs of significantly different means between job sites using Mann-Whitney tests ($p < 0.05$) (α-quartz).

respirable dust, and α-quartz at one job site (railway installation) were 0.88 mg/m^3 (GSD = 1.7), 0.23 mg/m^3 (GSD = 1.7), and 0.003 mg/m^3 (GSD = 1.8), respectively, versus on the other site (railway installation) 1.2 mg/m^3 (GSD = 1.8), 0.19 mg/m^3 (GSD = 1.7), and 0.003 mg/m^3 (GSD = 1.8), respectively (not shown). The differences between these exposures at these work sites were not significant. Statistical modeling of the determinants of respirable dust exposure found that iron work and demolition were associated with increased exposures, and iron work was associated with increased α-quartz exposure. These models explained 15 percent and 12 percent of the variance of the dust exposures, respectively. No significant models for total dust exposure were found (Table XII).

TABLE XI

Multiple linear regression analysis of determinants related to total dust, respirable dust, and α-quartz exposures in tunnel concrete workers

Agent	Determinants	Regression coefficient[A]	Standard error	p
Total dust	Intercept	1.00	0.051	<0.001
$R^2_{adj} = 0.36$, n = 95	Site A (yes/no)	0.675	0.093	<0.001
	Welding, %[B]	0.009	0.005	0.05
Respirable dust	Intercept	−0.502	0.128	<0.001
$R^2_{adj} = 0.57$, n = 94	Site A (yes/no)	1.06	0.157	<0.001
	Site B (yes/no)	0.379	0.144	<0.05
	Concreting, %	−0.003	0.002	0.06
	Demolition, %	−0.012	0.002	<0.001
	Demolition*Site B, %	0.010	0.004	<0.05
α-Quartz	Intercept	−5.67	0.246	<0.001
$R^2_{adj} = 0.85$, n = 56	Site A (yes/no)	3.32	0.269	<0.001
	Site B (yes/no)	3.10	0.333	<0.001
	Site C (yes/no)	1.83	0.365	<0.001
	Demolition, %	−0.007	0.003	<0.05
	Drilling, %	−0.011	0.005	0.05
	Outdoor, %	−0.031	0.011	<0.05

[A]The regression coefficient yields a factor with which the background level (intercept) should be multiplied to calculate the estimated geometric mean. For example, a worker at job site A who performs 100% welding during a work shift would have an estimated total dust exposure of: $\exp^{(1.00+0.675+0.009*100)} = \exp^{(1.00)} * \exp^{(0.675)} * \exp^{(0.009*100)} = 2.72 * 1.96 * 2.46 = 13.1$ mg/m^3.
[B]Percent time.

TABLE XII
Multiple linear regression analysis of determinants related to total dust, respirable dust, and α-quartz exposures in outdoor concrete workers

Agent	Determinants	Regression coefficient[A]	Standard error	p
Respirable dust	Intercept	−1.74	0.099	<0.001
$R^2_{adj} = 0.15, n = 40$	Iron work, %[B]	0.005	0.002	<0.05
	Demolition, %	0.005	0.002	0.06
α-Quartz	Intercept	−6.04	0.104	<0.001
$R^2_{adj} = 0.12, n = 40$	Iron work, %	0.005	0.002	<0.05

[A]The regression coefficient yields a factor with which the background level (intercept) should be multiplied to calculate the estimated geometric mean. For example, a worker who performs 60 percent iron work and 40 percent demolition during a work shift would have an estimated respirable dust exposure of: $\exp^{(-1.74+0.005*60+0.005*40)} = \exp^{(-1.74)} * \exp^{(0.005*60)} * \exp^{(0.005*40)} = 0.18 * 1.35 * 1.22 = 0.30$ mg/m^3.
[B]Percent time.

Electricians, Shaft Drilling Workers, and Support Workers

The geometric mean total dust, respirable dust, and α-quartz exposures for the electricians in the winter season were 1.5 mg/m^3 (GSD = 1.8), 0.67 mg/m^3 (GSD = 1.4), and 0.014 mg/m^3 (GSD = 2.1), respectively (not shown). For the spring season the geometric mean total dust, respirable dust, and α-quartz exposure was 1.1 mg/m^3 (GSD = 1.7), 0.85 mg/m^3 (GSD = 1.4), and 0.022 mg/m^3 (GSD = 1.2), respectively (not shown). These differences were not significant.

Determinants of exposure in shaft drilling and support work were not evaluated due to too few measurements in these groups (n = 7 and n = 16, respectively).

Perception of Exposure

Only job groups with measurements taken across all three evaluations of the work conditions (i.e., drill and blast; TBM; shotcreting; support) were evaluated. Fifteen percent of the measurements were reported by the workers to have been taken under conditions that were worse than usual, and 7 percent of the time conditions were reported to have been better than usual. When the conditions were reported to be worse than usual the most frequent explanation was that the ventilation system was not functioning. The geometric mean total dust, respirable dust, and α-quartz exposures when work conditions were reported to be "better than usual" were 2.7 mg/m^3 (GSD = 2.8), 0.86 mg/m^3 (GSD = 2.3), and 0.025 mg/m^3 (GSD = 6.2), respectively. The exposures when work conditions were reported to be "worse than usual" were 6.0 mg/m^3 (GSD = 2.0), 2.0 mg/m^3 (GSD = 1.7), and 0.10 mg/m^3 (GSD = 3.8), respectively. The exposures when work conditions were reported to be "as usual" were 3.9 mg/m^3 (GSD = 2.9), 1.4 mg/m^3 (GSD = 2.6), and 0.035 mg/m^3 (GSD = 4.8), respectively. The workers who reported "worse than usual" had significantly higher exposures than those who reported "better than usual" for all measured agents ($p < 0.05$) (not shown). There was also a trend indicating an increase in exposure from "better than usual" to "worse than usual." When analyzing the data by the four job groups, the same trends were found (not shown).

DISCUSSION

In this study we have investigated factors that influence dust exposures in tunnel construction as a basis for determining possible control measures and for further epidemiological analyses. Information on exposure levels of different tasks was obtained from the measurements and reports of the duration of the tasks by the construction workers at the end of the work shift because it was not possible to measure tasks separately. Information on other determinants was obtained from observation of the workers by the industrial hygienist and from the job site superintendent. The geometric mean exposure to total dust, respirable dust, and α-quartz for all tunnel workers was 3.5 mg/m^3 (GSD = 2.6), 1.2 mg/m^3 (GSD = 2.4), and 0.035 mg/m^3 (GSD = 5.0), respectively. A total of 15 percent of the total dust measurements, 5 percent of the respirable dust measurements, and 21 percent of the α-quartz measurements exceeded the Norwegian OELs of 10 mg/m^3, 5 mg/m^3, and 0.1 mg/m^3, respectively.[13] (The American Conference of Governmental Industrial Hygienists [ACGIH®] Threshold Limit Values [TLVs®] are 10 mg/m^3 inhalable dust, 3 mg/m^3 respirable dust, and 0.05 mg/m^3 α-quartz.)[14] TBM workers and shaft drilling workers were highly exposed to α-quartz, whereas shotcreting operators, TBM workers, and shaft drilling workers were highly exposed to total dust and respirable dust.

Working in the construction industry per se is not a useful indicator of exposure because construction work incorporates many different types of tasks that have a variety of exposures. Work site also is not useful because construction workers are typically employed at a large number of sites with differing exposure conditions throughout their career. Other investigators have concluded that tasks are important in exposure assessment in construction because "tasks, or specialized skills, form the single greatest thread of continuity in the dynamic environment of construction throughout an individual's lifetime."[6]

The workers were divided into job groups in which the workers performed similar tasks. These job groups appeared to be efficient for identifying similarly exposed workers because of the generally low GSDs (most groups were <3.0) and the fact that most groups had lower GSDs than the population as a whole.

Only the shaft drilling workers had larger GSDs but this job could not be broken down further because of small numbers. The job groups also provided information on which groups should be evaluated for exposure reduction strategies. The groupings do not on their own, however, indicate how to control the exposures of these workers. The statistical models developed in this study provide information on the types of situations (e.g., specific tasks or conditions) and control measures that could be considered for reducing exposures. The models may not be suitable for predictions of exposure levels in other underground construction settings as work organization and excavation methods can differ considerably between companies and countries. However, the strong determinants found here are likely to be important in other settings although their magnitude may differ.

Drill and Blast Workers

The drill and blast crew worked at the tunnel face close to the ventilation duct supplying fresh air to the work area. As expected, these workers excavating at the face were the job group with the lowest exposure to total dust (GM $= 2.3$ mg/m^3), respirable dust (GM $= 0.91$ mg/m^3), and α-quartz (GM $= 0.025$ mg/m^3). The use of a rock-drilling rig with a closed operator cab decreased exposure by 76 percent (total dust), 55 percent (respirable dust), and 85 percent (α-quartz) compared to a drill rig with no cab. When using a drill rig with no cab workers were positioned close to the drill head, which probably increased the likelihood of being exposed.

Contrary to expectation, only minor differences were found between open and closed cabs. This is probably due to exposure from other tasks that these workers performed outside the cab while being measured. These tasks, performed similarly by workers using open and closed cabs, were a substantial part of their job, being performed 86 percent of their total work time. In addition to the cab, modeling of the exposures showed that particular tasks were strong predictors of personal exposures to the three agents among the drill and blast workers. Some of the tasks (e.g., mechanical scaling, mucking, and transport) were expected a priori to have low exposures because they were performed using equipment with closed operator cabs. However, it was observed that the workers often had windows and doors open while performing these tasks, which probably explains why these tasks appeared to increase the exposure.

Another task unexpectedly associated with higher exposures—repairing the ventilation duct—does not generate dust by itself. However, it was observed that the tunnel construction work continued while the drill and blast workers did this repair work, and therefore the exposure was most likely due to increased ambient concentrations. Assisting with the drilling, repairing, performing miscellaneous work (tidying up work area, organize equipment), manual scaling, and rock bolting were tasks that appeared to generate less dust than drilling and the model confirmed this perception.

Shotcreting Operators

The shotcreting operators were among the highest exposed workers to total dust (GM $= 6.8$ mg/m^3) and respirable dust (GM $= 2.3$ mg/m^3). This high level is likely due to the dispersion of wet concrete as the concrete is accelerated through the nozzle by compressed air. As expected, use of a closed cab on the rig had the most important effect on exposure levels. Total dust and respirable dust exposure levels were reduced by more than 70 percent by using a closed cab compared to no cab.

When shotcrete was applied onto the tunnel walls (at the tunnel face) before the breakthrough of the tunnel, it was typically done at night after other workers (e.g., drill and blast workers) had finished their evening shift. When the excavation had been completed, that is, after breakthrough, shotcrete was applied simultaneously with other finishing tasks without mechanical ventilation. Whether the job was performed before or after the breakthrough of the tunnel had a large effect on the exposure level, but contrary to expectation, this was found only for total dust (8.5 mg/m^3 vs. 1.9 mg/m^3, respectively) and not for respirable dust or α-quartz. The air exchange is expected to substantially increase after breaking through to the other side because of natural air currents, which may carry away the dust generated by the shotcreter. However, the increased air flow may also transport dust generated by other workers into the breathing zone of the shotcreter. Because we did not obtain information on the concentration and particle size distribution of dust in the ambient air we can only speculate on possible explanations. The results, however, suggest that the ambient air could have a larger proportion of respirable dust than the dust generated by the shotcreter. This seems likely as coarse particles may have settled from the ambient air before reaching the shotcreters.

Several chemical additives were added to the concrete. One of them, an accelerator, was used to improve the adhesion of the concrete to the rock surface and to speed up the setting and hardening of the concrete. It was added to the concrete during the spraying process in proportions of three to eight percent of the cement weight. There was a small and statistically nonsignificant difference between the two types of accelerators with respect to total and respirable dust exposure. Anecdotal information from the workers under study indicated that the alkali free accelerator produced less dust and this was supported by our data. This should be investigated further also because the waterglass (alkaline) accelerator may be more irritating to the respiratory system than the alkali-free accelerator due to its higher pH (pH 11–13 compared with pH of 2–3). The waterglass accelerator is most commonly used in Norway.

None of the determinants evaluated had a significant influence on the shotcreters' α-quartz exposure. The amount of α-quartz in shotcrete dust varied from 0.1–3.0 percent between job sites. This variability probably depends on the mix of the concrete and provided an additional source of variation that increased the unexplained variance, which may have obscured the effects of other determinants of α-quartz.

TBM Workers

The TBM workers operated a tunnel boring machine that drills the entire cross-section of the tunnel. The rock was broken up by the drill head, loaded automatically on a conveyor belt, and transported out of the tunnel. The TBM workers were highly exposed to total dust (GM = 6.2 mg/m^3), respirable dust (GM = 2.0 mg/m^3), and α-quartz (GM = 0.39 mg/m^3). The dust exposure levels were significantly higher when the TBM operated than when it did not. When the machine was not operated, the workers did various types of repair work on the TBM and ventilation ducts or laid down rails to transport workers and equipment to the tunnel face, resulting in low exposures. The TBM had a closed operator cab, but the operator seldom kept the door closed because the conveyor belt needed to be monitored. A statistical difference was found in respirable dust exposures between seasons with highest in the winter and lowest in the summer, a pattern also seen for total and α-quartz. We have no explanation for this phenomenon. The multivariate models did not explain much of the variability in exposure (10%–17%), probably because operation of the TBM was the most important source of dust exposure. There were small differences among the tasks, although supervision of the loading rock and "miscellaneous tasks" were associated with slightly increased exposure levels.

Concrete Workers

Concrete workers do iron and carpentry work either in tunnels or in the outdoor air. The concrete workers first erect steel reinforcement bars. Welding and torch cutting of the steel is done intermittently but frequently. A wooden form is constructed around the bars, and the form is cleaned with pneumatic air and sprayed with mineral oil. Moist concrete is poured into the wood form and allowed to harden. Finally, the wood form is demolished. The concrete surface is occasionally sandblasted by the workers to provide a smooth surface.

Concrete workers employed at one of the tunnel sites (site A) were exposed to much higher dust concentrations than workers at other sites. The reason for this association was probably that this site was located in a downtown area. The employer had problems with placement of the ventilation fans and ducts because of complaints from the neighbors about noise emitted from the fans. The construction site was also complex, having connections among several tunnels and a shaft, which made the tunnel difficult to ventilate. Sandblasting was performed occasionally, and the dust generated from this operation was deposited in the work area. Lack of good vacuuming practices allowed this dust to be re-entrained into the tunnel atmosphere. That sandblasting was not performed at other sites provides another explanation for the differences in exposure levels between the sites. By modeling the exposures it was found that job site and various tasks explained a substantial part of the variance of personal exposures to total dust, respirable dust, and α-quartz (36%–85%). An interaction between the task demolition and job site B was found for respirable dust, indicating increased exposure when performing demolition at site B compared to other sites. A possible explanation for this result is that at job site B, in addition to wooden forms, large scaffoldings were constructed and demolished, whereas at other sites scaffoldings were not constructed. When the scaffoldings were demolished, deposited dust may have been redispersed throughout the work area leading to high exposure of these workers.

As expected, substantially lower exposure levels were observed among outdoor concrete workers compared to those who worked in the tunnels. The models explaining the exposure of the tunnel concrete workers and the outdoor concrete workers were different, although the workers in these two groups performed the same type of work. A likely explanation is that in the tunnels, the concrete workers were subject to bystander exposures because other job groups were working simultaneously, in contrast to the outdoor workers. Furthermore, the ventilation of the tunnels was probably less effective in removing dusts from the area than the natural air currents occurring outdoors.

Self-Assessment of Exposure

The workers were asked after the sampling about their perception of work conditions during the day to investigate if they were able to assess their own work atmosphere qualitatively. The majority of answers was that the exposure condition was "as usual," indicating that tunnel workers are used to large variations in exposure conditions (i.e., GSD = 2.9 for total dust). However, the results suggest that workers can distinguish between normal and higher-than-normal exposure, which can be used in the evaluation of the effectiveness of controls when workers complain of dusty conditions.

Concluding Remarks

The use of ventilated, closed cabs seems to be the single most important control measure for lowering exposures for these workers. The effectiveness of a cab depends on the type of filter installed at the air intake, the cleanliness of the cab, and the practice of keeping doors and windows closed. The cab will also protect the worker against noise and draft. Cab use is important in several of the tasks performed in underground construction (mechanical scaling, mucking, drilling, shotcreting, and transport).

The type of drilling equipment can greatly affect the exposure. The TBM machines produced greater amounts of dust compared to the drill rigs used by the drill and blast crew. Effects of different dust control systems on the TBM machine and the use of water to reduce dust dispersion throughout the work area should be evaluated.

Although only investigated for the shotcreting operators, the phase of the production process (i.e., before or after breakthrough of the tunnel) and whether jobs are performed simultaneously with other jobs are expected to be important determinants of exposure of several jobs (i.e., concrete work, electrical work). An investigation of the effect of chemical admixtures on dust exposure in shotcreting and improvement of the ventilation system (i.e., use of local exhaust ventilations) should be subject for further study.

By modeling the exposures it was found that tasks were important determinants of exposure in several job groups. If restricting time used on high exposed tasks is not feasible, the use of personal protective equipment should be enforced when performing such tasks.

These data were collected for assessing exposures in an epidemiological study. Analyses of the data identified several important determinants that will be considered for estimating exposures. In further epidemiological analyses, information on job group, cab use, duration of task performed, and a distinction between various drilling equipment seems reasonable when estimating exposures. Such determinants may also be important in other epidemiological studies of tunnel workers and therefore should be included in any questionnaire administered to the workers.

CONCLUSIONS

The results show that job group, tasks, and equipment are important determinants of dust exposure. The use of ventilated, closed cabs seems to be the single most important control measure for lowering exposures.

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